A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)

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LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation, primitive equation ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. Currently, both modeling systems are identical and extensively used by the research and operational communities around the world. Our aim is to produce an open-source, terrain-following, ocean community model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics/stability/sensitivity, which is highly relevant to ONR objectives. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications.

OBJECTIVES

The main objectives of this project are:

- To develop and test a robust ocean modeling framework for relocatable coastal ocean prediction applications.
- To develop algorithms and tools for improving U.S. Navy coupled atmosphere-ocean forecasting capabilities.
- To develop advanced 4-dimension Variational (4D-Var) data assimilation capabilities and analysis algorithms for observation sensitivity, observation impact, adaptive sampling, and forecast errors and uncertainties.
- To develop adjoint-based ocean prediction analysis tools similar to those available in Numerical Weather Prediction (NWP) for the atmosphere for circulation stability, sensitivity analysis, and ensemble prediction.
- To develop multiple grid nesting capabilities to resolve complex geographical regions and circulation regimes.

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- To develop the framework for multiple model (atmosphere, sea-ice, waves) coupling using available libraries.
- To provide the ocean modeling community with the current state-of-the-art knowledge in dynamics, numerical schemes, and computational algorithms technology. ROMS is freely distributed (www.myroms.org) to the Earth's modeling community and has thousands of users worldwide.
- To engage the ocean modeling community by organizing annual scientific workshops and training.

APPROACH

ROMS/TOMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski *et al*., 2004; Warner *et al*., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom.

Several adjoint-based algorithms exist to explore the factors that limit the predictability of the circulation in regional applications for a variety of dynamical regimes (Moore *et al*., 2004, 2009). These algorithms use the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. The resulting singular vectors can be used to construct ensembles of forecasts by perturbing initial and boundary conditions (optimal perturbations) and/or surface forcing (stochastic optimals). Perturbing the system along the most unstable directions to the state-space yields information about the first (ensemble mean) and second (ensemble spread) moments of the probability density function. Given an appropriate forecast skill measure, the circulation is predictable if low spread and unpredictable if large spread.

ROMS/TOMS uniquely supports three different 4D-Var data assimilation methodologies (Moore *et al.*, 2011a, b): a primal form of the incremental strong constraint 4D-Var (I4D-Var), a strong/weak constraint dual form of 4D-Var based on the Physical-space Statistical Analysis System (4D-PSAS), and a strong/weak constraint dual form of 4D-Var based on the indirect representer method (R4D-Var). In the dual formulations, the search for the best ocean circulation estimate is in the subspace spanned only by the observations, as opposed to the full space spanned by the model as in the primal formulation. Although the primal and dual formulations yield identical estimates of the ocean circulation for the same *a priori* assumptions, there are practical advantages and disadvantages to both approaches (Moore *et al.*, 2011a, b, c). To our knowledge, ROMS/TOMS is the only open-source, ocean community-modeling framework supporting all these variational data assimilation methods and other sophisticated adjoint-based algorithms.

There are several biogeochemical models available in ROMS. In order of increasing ecological complexity these include three NPZD-type models (Franks *et al.*, 1986; Powell *et al.*, 2006; Fiechter *et al.*, 2009), a nitrogen-based ecosystem model (Fennel *et al.*, 2006, 2008), a Nemuro-type lower level ecosystem model (Kishi *et al*., 2007), and a bio-optical model (Bissett *et al.*, 1999).

ROMS includes a sediment-transport model with an unlimited number of user-defined cohesive (mud) and non-cohesive (sand) sediment classes (Warner *et al.*, 2008). Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for erosion, and erodibility constant. A multi-level bed framework tracks the distribution of every size class in each layer and stores bulk properties including layer thickness, porosity, and mass, allowing the computation of bed morphology and stratigraphy. Also tracked are bed-surface properties like active-layer thickness, ripple geometry, and bed roughness. Bedload transport is calculated for mobile sediment classes in the top layer.

ROMS is a very modern and modular code written on F90/F95. It uses C-preprocessing to activate the various physical and numerical options. The parallel framework is coarse-grained with both shared-memory (OpenMP) and distributed-memory (MPI) paradigms coexisting in the same code. Because of its construction, the parallelization of the adjoint is only available for MPI. Several coding standards have been established to facilitate model readability, maintenance, and portability. All the state model variables are dynamically allocated and passed as arguments to the computational routines via dereferenced pointer structures. All private arrays are automatic; their size is determined when the procedure is entered. This code structure facilitates computations over nested grids (Warner *et al.*, 2011).

WORK COMPLETED

Three types of nesting capabilities have been designed and coded in ROMS: (i) *refinement* grids which provide increased resolution (3:1, 5:1, or 7:1) in a specific region; (ii) *mosaics* which connect several grids along their edges, and (iii) *composite* grids which allow overlap regions of aligned and non-aligned grids. The *mosaic* and *composite* grid code infrastructures are identical. The differences are geometrical and primarily based on the alignment between adjacent grids. All the *mosaic* grids are exactly aligned with the adjacent grid. In general, the *mosaic* grids are a special case of the *composite* grids.

The nesting development in ROMS was divided into three phases due to its complexity. **Phase I** included substantial modifications of the numerical kernels to allow a generic treatment of the spatial horizontal operators in the nesting contact regions. **Phase II** included an overhaul of ROMS lateral boundary conditions to facilitate, in a generic way, their processing or not in applications with nested grids. **Phase III** included the data managing and time-stepping infrastructure for one or more nesting layers. These phases are described in detail in last year's (FY11) annual report. **Phase I** was released to the community as ROMS **3.5** on April 25, 2011 whereas **Phase II** was released as ROMS **3.6** on September 23, 2011. The coding of **Phase III** was completed during this fiscal year cycle and is currently under extensive testing before it is released to the user community.

RESULTS

During this fiscal year (FY12), the primary focus was the development and coding of ROMS nesting **Phase III**. Several modules were added to process the information that is required in the contact regions, what information needs to be exchanged from/to another grid, and when to exchange it.

A contact region is an extended section of the grid that overlays or is adjacent to a nested grid. A contact point is a grid cell inside the contact region. Each contact region has a receiver grid and donor grid. The contact points of the receiver grid are processed using the donor grid cell containing the contact point. The contact points are coincident if the receiver and donor grids occupy the same position. If coincident grids, the receiver grid contact point data is just filled using the donor data. Otherwise (if not coincident) the receiver grid data is linearly interpolated from the donor grid cell containing the contact point. There is a duality in ROMS nested grids: data donor in one contact region and data receiver in its conjugate contact region. The exchange of information is always two-way. This explains why we prefer to use the donor and receiver categories instead of the usual parent and child descriptions found in the literature.

The contact points are processed outside of ROMS and all the connectivity within nested grids is read from an input NetCDF file. This facilitates the configuration of various grid Sub-Classes. It tremendously simplifies the processing of such points in parallel computations. It also gives the user full editing control of the contact points. The contact points need to be set-up once for a particular application. Several Matlab utilities were developed to process ROMS nested grids capabilities. These scripts are too technical to be described here, but detailed information can be found in WikiROMS (https://www.myroms.org/wiki/index.php/Matlab_Scripts).

In grid *refinement* applications, the information is exchanged at the beginning of the full time-step (top of **main2d** or **main3d**). Contrarily, in *composite* grid applications, the information is exchanged between each sub-time step call in **main2d** or **main3d**. That is, the composite donor and receiver grid need to sub-time step the 2D momentum equations before any of them start solving and coupling the 3D momentum equations. Therefore, the governing equations are solved and nested in a synchronous fashion. The concept of *nesting layers* is introduced to allow applications with both *composite* and *refinement* grid combinations, as shown in Figure 3a for the Refinement and Partial Boundary Composite Sub-Class. Here, two nesting layers are required. In the first nesting layer, the composite grids 1 and 2 are synchronously sub-time stepped for each governing equation term. Then, in the second and last nesting layer, the refinement grid 3 is time stepped and the information between donor (1) and receiver refinement (3) grids are exchanged at the beginning of the time step for both contact regions: coarse-to-fine and fine-to-coarse.

The ROMS nested grid design includes three Super-Classes and several Sub-Classes:

1. Composite Grids Super-Class:
    a. Mosaic Grids Sub-Class
    b. Composite Overlap Grids Sub-Class
    c. Complex Estuary Composite Grids Sub-Class
    d. Partial Boundary Composite Grids Sub-Class
2. Refinement Grids Super-Class:

a. Single Refinement Sub-Class
b. Multiple Refinement Sub-Class

3. Composite and Refinement Combination Super-Class:

    a. Refinement and Partial Boundary Composite Sub-Class
    b. Complex Estuary Refinement-Composite Sub-Class

Hence, there are several possibilities and combinations. The design is flexible enough to allow complex nested grid configurations in coastal applications. These capabilities are better illustrated with diagrams of the different Sub-Classes shown in Figures 1, 2, and 3. The diagrams are all in terms of computational coordinates (ξ, η) or fractional (*i, j*) coordinates. Therefore we have squares and rectangles that may map to physical curvilinear coordinates. Here, **Ngrids** is the number of nested grids, **NestLayers** is the number of nested layers, **GridsInLayer** is a vector with the number of grids in each nested layer, and **Ncontact** is the number of nesting contact regions, (**Ngrids**-1)*2.

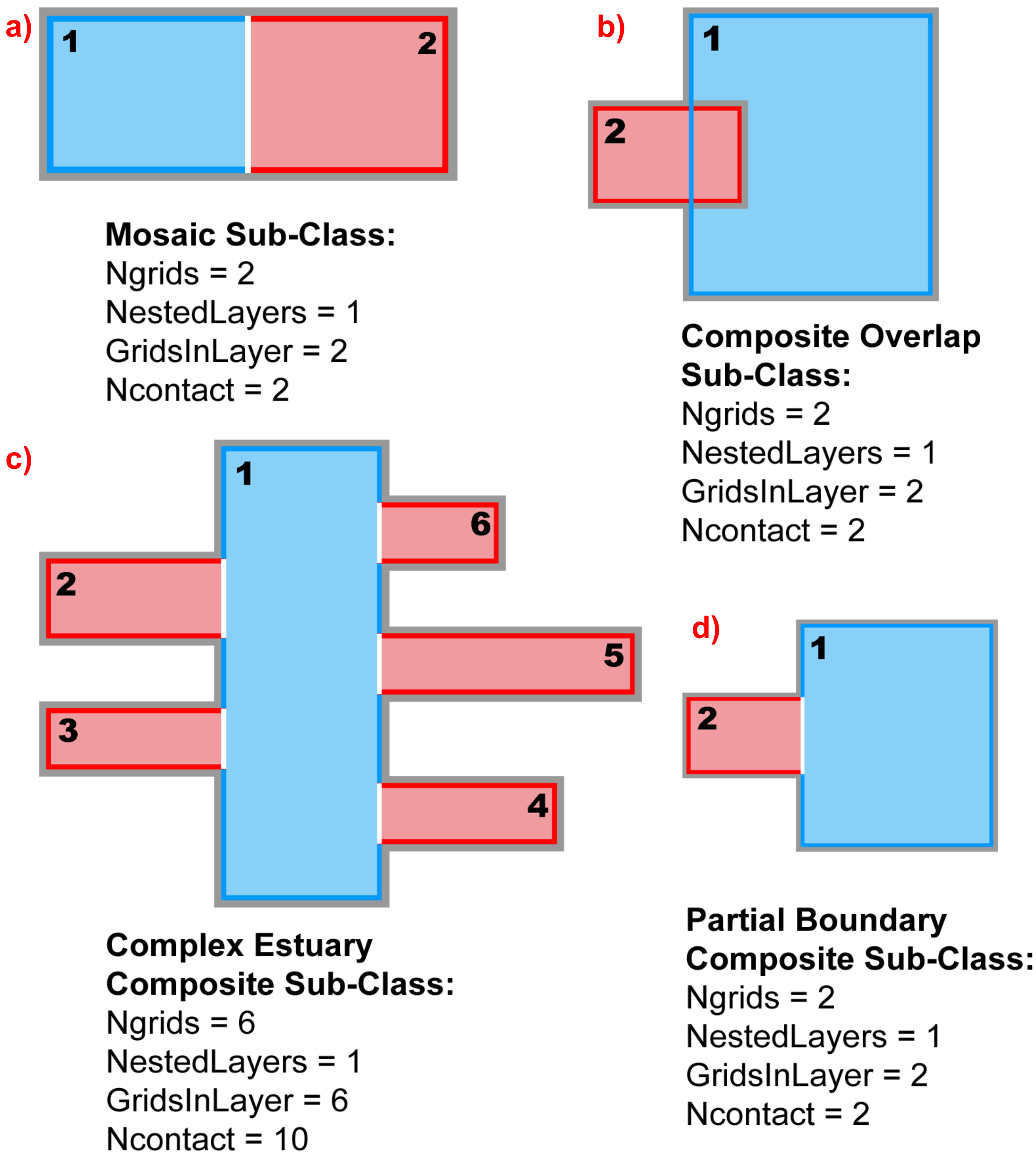


Figure 1: Composite Grids Super-Class: a) Mosaic Sub-Class, b) Composite Overlap Sub-Class, c) Complex Estuary Composite Sub-Class, and d) Partial Boundary Composite Sub-Class. Each diagram shows the number of nested grids (Ngrids), number of nested layers (NestedLayers), number of grids in each nested layer (GridsInLayer), and number of contact regions (Ncontact).

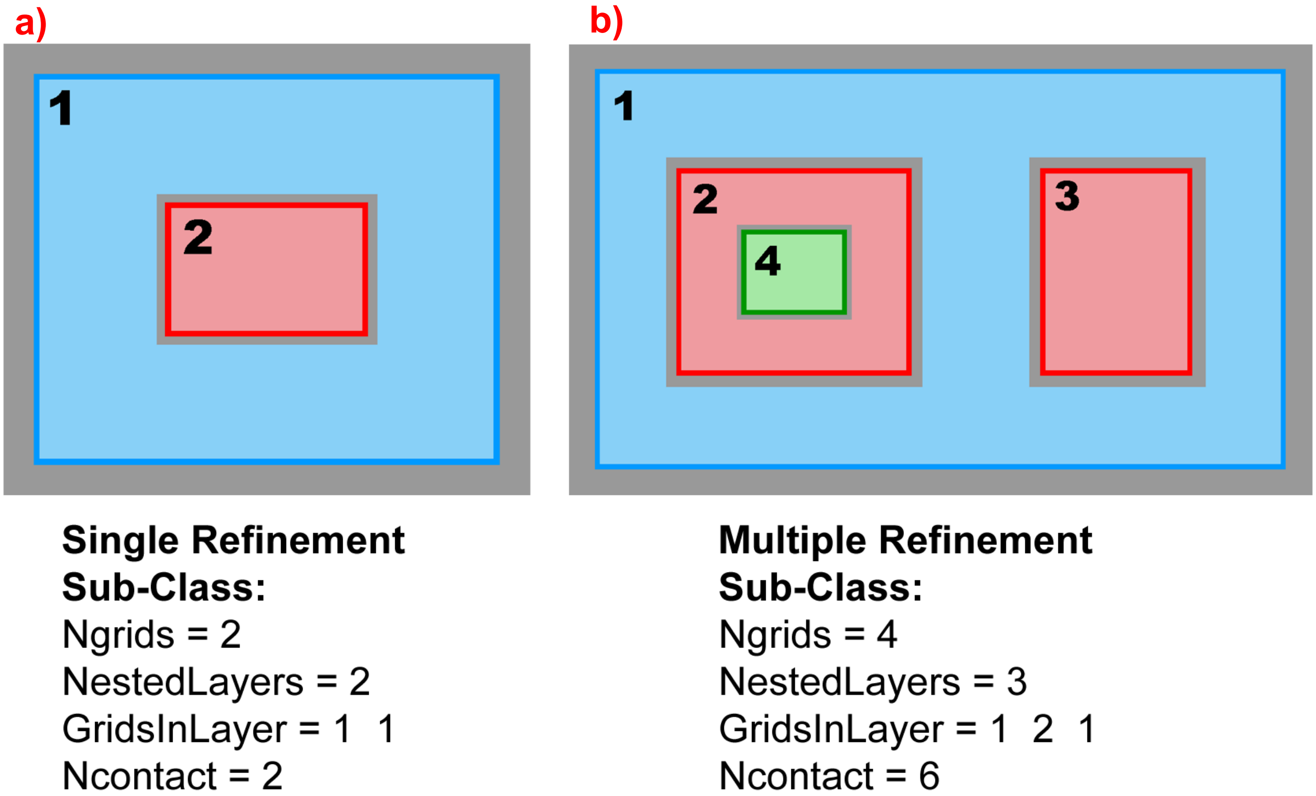
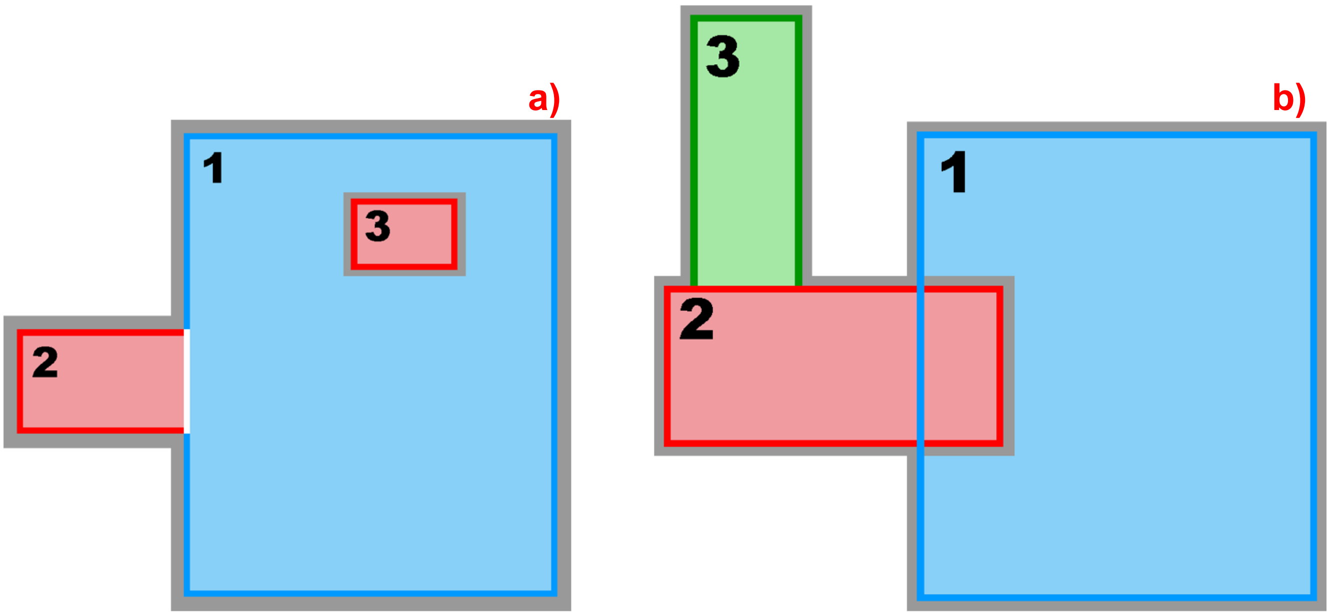


Figure 2: Refinement Super-Class: a) Single Refinement Sub-Class and b) Multiple Refinement Sub-Class. Each diagram shows the number of nested grids (Ngrids), number of nested layers (NestedLayers), number of grids in each nested layer (GridsInLayer), and number of contact regions (Ncontact).



Refinement and Partial Boundary Composite Sub-Class:
Ngrids = 3
NestedLayers = 2
GridsInLayer = 2 1
Ncontact = 4

Complex Estuary Refinement-Composite Sub-Class:
Ngrids = 3
NestedLayers = 2
GridsInLayer = 1 2
Ncontact = 4

Figure 3: Composite and Refinement Combination Super-Class: a) Refinement and Partial Boundary Composite Sub-Class and b) Complex Estuary Refinement-Composite Sub-Class. Each diagram shows the number of nested grids (Ngrids), number of nested layers (NestedLayers), number of grids in each nested layer (GridsInLayer), and number of contact regions (Ncontact).

Figure 4 shows a realistic nesting configuration in a US East Coast application using the Complex Estuary Refinement-Composite Sub-Class. It illustrates ROMS nesting capabilities with complex coastlines and estuaries. The coarser grid, ESPRESSO (130 x 82), has an average resolution of dx=7.5km, dy=5.8km. The nested grids (ρ-points mesh) are color coded for convenience to show the strategy used to better resolve the Delaware and Chesapeake Estuary Systems. The red and green are refinement grids whereas blue and magenta are composite grids. The refinement ratio is 1:7. An intermediate 1:7 refinement grid is created using Matlab script *coarse2fine.m* that included both the Delaware and Chesapeake Estuary Systems. Then, the Matlab script *grid_extract.m* is used to extract the Delaware Bay refinement grid (58 x 142) and Delaware River composite grid (42 x 55). Similarly, *grid_extract.m* is used to extract the Chesapeake Bay outer refinement grid (135 x 142) and Chesapeake Bay inner composite grid (233 x 212).

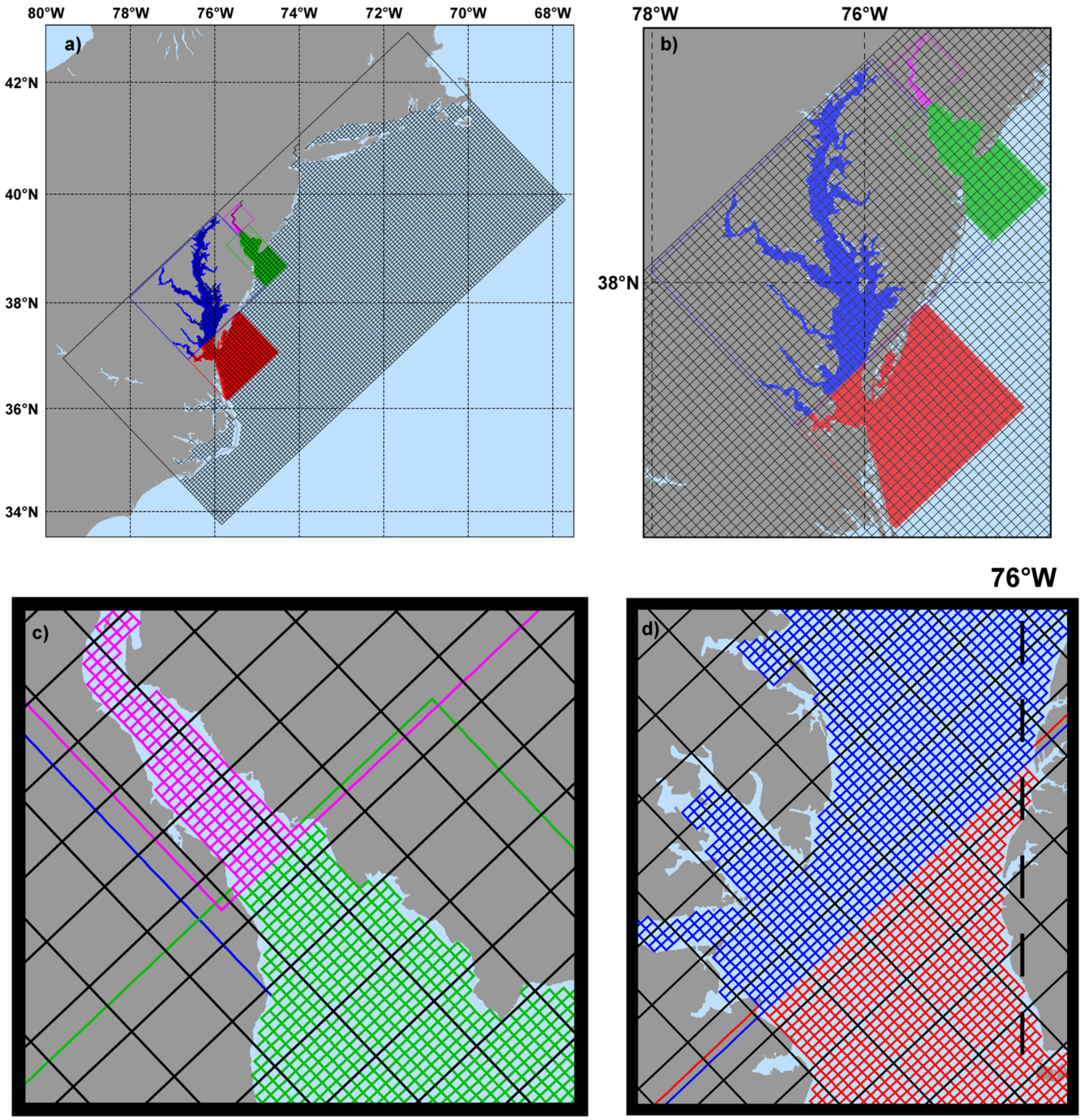


Figure 4: A US east coast example of the Complex Estuary Refinement-Composite Sub-Class: a) full nested grid configuration, b) zoom of the Delaware and Chesapeake estuaries refinement (green and red) and composite (magenta and blue) grids, c) further zoom of Delaware estuary contact region between refinement and composite connected grids, and d) further zoom of Chesapeake estuary contact region between refinement and composite connected grids.

The next user workshop will be held in Rio de Janeiro, Brazil, October 22-24, 2012. A special fourth day (October 25) has been added to focus modern observational, modeling, and data assimilation systems, which includes special lectures and discussions. Over 100 participants are expected this year; far more than at any previous workshop.

IMPACT/APPLICATIONS

This project will provide the ocean modeling community with a freely accessible, well documented, open-source, terrain-following, ocean model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics, stability, and sensitivity.

TRANSITIONS

The full transition of ROMS/TOMS to the operational community is likely to occur in the future. However, the ROMS/TOMS algorithms are now available to the developers and scientific and operational communities through the website http://www.myroms.org/.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (H. Arango) closely collaborates with A. Moore (adjoint-based algorithms) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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